# Are Dumbbell Brightest Cluster Members Signposts to Galaxy Cluster Activity?

*K. A. Pimbblet*[A,B]

[A] Department of Physics, University of Queensland, Brisbane, Queensland, QLD 4072, Australia

[B] Email: pimbblet@physics.uq.edu.au

**Abstract:** We assemble a sample of galaxy clusters whose brightest members are dumbbell galaxies and compare them with a control sample in order to investigate if they are the result of recent mergers. We show that the dumbbell sample is no more likely than other clusters to exhibit subclustering. However, they are much more likely to have at least one dumbbell component possessing a significant peculiar velocity with respect to the parent cluster than a non-dumbbell brightest cluster member. We interpret this in the context of seeing the clusters at various stages of post-merger relaxation.

**Keywords:** galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: evolution

## 1 Introduction

Brightest cluster member (BCM) galaxies have historically held a special place in both the theoretical and observational study of galaxy evolution and formation since they are believed to be directly connected with the conditions in the cluster that they reside in. Consider, for instance, a BCM that is located at the bottom of the gravitational well of a galaxy cluster: there, a process such as cannibalism (e.g. Ostriker & Tremaine 1975) would be at maximum efficiency there and we would be likely to observe BCMs with multiple cores (e.g. Laine et al. 2003; Yamada et al. 2002; Oegerle & Hill 2001; Dubinski 1998; Lauer 1988; Hoessel & Schneider 1985). However, if a more hierarchical paradigm is correct, then the BCM should have formed through multiple minor merger events in a subgroup that was originally outside the cluster centre. It would have then subsequently merged with the rest of the cluster (Merritt 1985), yielding several observational road-signs such as high peculiar velocities for the BCM and cluster substructure (see Woudt et al. 2008; Pimbblet et al. 2006; Oergle & Hill 2001; Pinkney et al. 1996; Quintana et al. 1996; Valentijn & Casertano 1988).

Cases of dumbbell galaxies as BCMs (e.g. Gregorini et al. 1994; 1992) are doubly interesting for these reasons – these galaxies should be an indicator of the pre-virialization scenario and should therefore be accompanied by significant substructure indicative of recent cluster merger activity. Indeed, Quintana et al. (1996) present evidence for a dumbbell system where the two components of the BCM *each* belong to major sub-groups that are undergoing a merger (see also de Souza & Quintana 1990).

What is unclear is whether dumbbell BCM clusters in general are special? Does the presence of a dumbbell BCM point toward observable cluster activity such as subclustering (Quintana et al. 1996) and large BCM peculiar velocities (Pimbblet et al. 2006) as would be found during a merger event? If so, then what stage is the merger event at? In order to make a pass at answering these questions, this work assembles a modest sample of dumbbell BCMs from Gregorini et al. (1992) and a control sample derived from the 2 degree field galaxy redshift survey (2dFGRS; Colless et al. 2001).

The format of this paper is as follows. In Section 2 we fully describe our derived dumbbell sample and control sample. In Section 3, we ask whether clusters with dumbbell BCMs are more likely to have substructuring than any other clusters and then in Section 4, we examine the incidence of significant peculiar velocities in our samples are different. We summarize our findings in Section 5. Throughout this work, we adopt a cosmological concordance model with values of $H_0 = 70$ kms$^{-1}$Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

## 2 The Samples

The Gregorini et al. (1992) sample claims to be a volume limited & homogeneous sample of dumbbell BCM galaxies which should be ideal for our purposes. It is based on the Abell catalogue (Abell 1958; Abell et al. 1989) and is complete out to a comoving distance of 210h$^{-1}$ Mpc (Gregorini et al. 1992). In addition, they state there are no possible selection biases present in this sample that would have prevented the successful detection and identification of dumbbell galaxies for this sample (Gregorini et al. 1992; see also Scaramella et al. 1991). There are a couple of debatable clusters that could have been added to this sample (e.g. Abell 3323; Gregorini et al. 1994), but were left out. We do not view the exclusion of these clusters as having a significant impact on the ensemble. However, our review of the available literature redshifts demonstrates that this sample does contain several clusters with $z > 0.1$ (Table 1) due to earlier cluster redshifts being under-estimated. We do not regard this as a major impediment to the present investigation either, since the time evolved between $z \sim 0.07$ and $z \sim 0.10$ is much smaller (i.e. $< 0.5$ Gyr) than the expected time it would take for sub-clusters to fully merge (Lacey & Cole 1993). For this work, we restrict ourselves to the

complete sample of dumbbell galaxies – Table 1 from Gregorini et al. (1992; herein the dumbbell sample) – with one exception: Abell 3653. Abell 3653 is listed by Gregorini et al. (1992) as only a 'possible' dumbbell BCM. However, a combination of observations made by Postman & Lauer (1995) and Pimbblet et al. (2006) show that this cluster should also be considered to be a confirmed dumbbell BCM galaxy (Figure 1) and we include it in the present dumbbell sample.

Redshift information for the dumbbell sample is initially obtained by downloading all redshifts within 30 arcmin of each cluster from the NASA Extra-galactic Database (NED). At $z \sim 0.1$, this corresponds to a radius of 1.6 Mpc from the cluster centre. Several clusters in the resultant dumbbell sample (Abell 2824, 3098, 3368, 3397, & 3740) generate very few members ($N < 20$) within 30 arcmin ($\approx$ an Abell radius) and are eliminated from the final sample at this stage since it is likely that any subclustering or cluster velocity dispersion measurement would be unreliable (Girardi et al. 1993). For the remaining sample, we compute the mean cluster velocity and velocity dispersion ($\sigma$) using the 'gapping' procedure of Zabludoff et al. (1990; 1993) and tabulate these values in Table 1. The final sample yields 13 dumbbell BCM galaxy clusters for us to work with that have a range of velocity dispersions consistent with large and massive clusters (cf. Ebeling et al. 2007).

Our control sample is obtained from the 2dFGRS cluster sample of De Propris et al. (2002; see Colless et al. 2001 for a description of this survey). This is essentially a complete catalogue at $cz < \sim 35000$ km s$^{-1}$ of Abell (Abell 1958; Abell et al. 1989) clusters. In order to attempt to match the relatively high velocity dispersions in the dumbbell sample, we restrict the control sample to only those clusters with a high X-ray luminosity ($L_X > 0.5 \times 10^{44}$ erg s$^{-1}$; Ebeling et al. 1996; Cruddace et al. 2002). We also trim from this sample any clusters with poor completeness levels (i.e. less than 20 galaxies within an Abell radius of the cluster centre). Our final control sample consists of 14 clusters and is presented in Table 2 with mean velocities and velocity dispersions sourced from De Propris et al. (2002). Although the control sample has a smaller absolute range of $\sigma$ (597–1038 kms$^{-1}$) than the dumbbell cluster sample (455–1376 kms$^{-1}$), the median values (783.5 kms$^{-1}$ and 825 kms$^{-1}$ respectively) are very similar. The average redshift of the control sample ($cz = 26010$ kms$^{-1}$) is also somewhat higher than the dumbbell sample ($cz = 18854$ kms$^{-1}$). In look-back time this is barely 0.3 Gyr, so again we do not regard this as significant for this work due to the comparative time taken for clusters to violently relax after a merger event (Lacey & Cole 1993). With the control sample being sourced from 2dFGRS, we ensure that all the constituent galaxies are very homogeneously sampled down to $b_J = 19.45$ (Colless et al. 2001); albeit not at 100% completeness levels (see De Propris et al. 2002). Conversely, our dumbbell sample is a collection of diverse redshifts from multiple sources each with different purposes and associated selection limits imposed (see Table 1). We also eyeball the BCMs in the control sample to ensure that they are not dumbbells themselves that are outside the Gregorini et al. (1992) selection limits. Only two of them give us cause for concern: Abell 2811 has a nearby faint companion, but would not be considered a dumbbell in the definition of Gregorini et al. (1992); Abell S1136 has multiple galaxies near to the BCM that may be interacting with it, but again it is not a dumbbell and its removal from the control sample does not affect our conclusions.

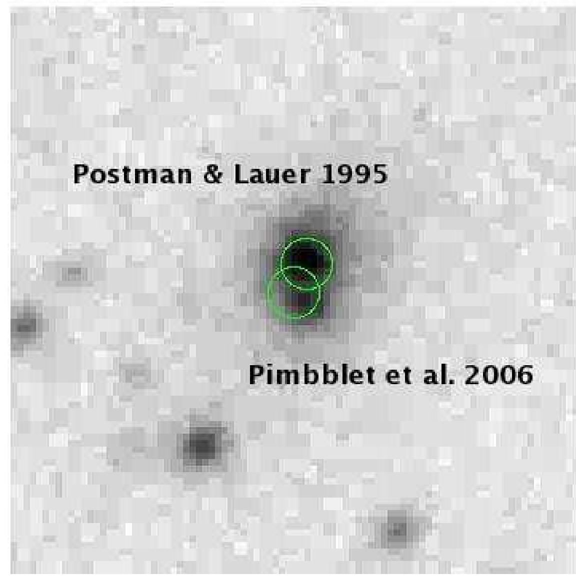


Figure 1: Spectroscopic observations of the components of the dumbbell BCM galaxy in Abell 3653 have been made by Postman & Lauer (1995) and Pimbblet et al. (2006); the circles in the plot denote the location of where the redshift was taken. They give redshifts of $z = 0.1091 \pm 0.0003$ and $z = 0.1099 \pm 0.0002$ respectively. Since both components are within $2\sigma$ of each other, we consider this galaxy to be a confirmed dumbbell BCM galaxy for the purposes of this work.

## 3 Substructure

In order to place the clusters onto a common scale and perform a meaningful comparison of subclustering, we use a virial radius estimator derived by Girardi et al. (1998): $R_v = 0.002\sigma h_{100}^{-1}$ Mpc. Cluster members are then defined to be those galaxies whose velocity is within $3\sigma$ of the cluster velocity. We add the caveat that although this approximation's validity for semi-virialized systems may not be ideal, it is sufficient for our purposes of placing the clusters on to a $\sim$common scale.

For the cluster centres, we use the quoted NED cluster centres – this choice of cluster centre is somewhat arbitrary, but it will not dramatically affect the final subclustering result since we are sampling the

Table 1: The dumbbell cluster sample[a].

| Cluster | RA (J2000) | Dec (J2000) | N(30')[b] | $cz$ (kms$^{-1}$) | $\sigma$ (kms$^{-1}$) | $R_V$ (Mpc) | N$_{R_V}$ | $\Delta_{R_V}$ | P($\Delta$)$_{R_V}$ | N$_{2R_V}$ | $\Delta_{2R_V}$ | P($\Delta$)$_{2R_V}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abell 2860 | $1^h4^m20.60^s$ | -39$^o$2961.4" | 59 | 31738$\pm$97 | $741^{+80}_{-60}$ | 1.48 | 28 | 76 | 0.990 | 45 | 148 | 0.985 |
| Abell 2911 | $1^h26^m12.87^s$ | -37$^o$3381.8" | 50 | 24110$\pm$102 | $720^{+85}_{-63}$ | 1.44 | 34 | 30 | 0.720 | 50 | 41 | 0.959 |
| Abell 3151 | $3^h40^m27.73^s$ | -28$^o$2543.0" | 68 | 19992$\pm$124 | $1013^{+101}_{-78}$ | 2.03 | 60 | 115 | 0.009 | 103 | 230 | 0.016 |
| Abell 3266 | $4^h31^m11.92^s$ | -61$^o$1462.6" | 286 | 17852$\pm$81 | $1376^{+61}_{-54}$ | 2.75 | 248 | 277 | 0.313 | 399 | 524 | <0.001 |
| Abell 0533 | $5^h1^m30.79^s$ | -22$^o$2202.4" | 27 | 13932$\pm$229 | $1191^{+208}_{-136}$ | 2.38 | 35 | 92 | <0.001 | 52 | 146 | <0.001 |
| Abell 3391 | $6^h26^m15.43^s$ | -53$^o$2452.3" | 104 | 16070$\pm$127 | $1294^{+101}_{-82}$ | 2.59 | 131 | 207 | <0.001 | 241 | 440 | <0.001 |
| Abell 3528 | $12^h54^m18.36^s$ | -29$^o$75.6" | 146 | 16219$\pm$87 | $1047^{+67}_{-56}$ | 2.09 | 145 | 194 | 0.017 | 236 | 327 | <0.001 |
| Abell 3532 | $12^h57^m19.08^s$ | -30$^o$1332.7" | 167 | 16504$\pm$60 | $780^{+47}_{-40}$ | 1.56 | 117 | 150 | 0.061 | 233 | 303 | 0.018 |
| Abell 3535 | $12^h57^m48.60^s$ | -28$^o$1752.1" | 55 | 20190$\pm$61 | $455^{+51}_{-38}$ | 0.91 | 37 | 46 | 0.041 | 53 | 78 | 0.010 |
| Abell 3570 | $13^h46^m50.88^s$ | -37$^o$3298.3" | 31 | 11261$\pm$83 | $463^{+74}_{-50}$ | 0.93 | 19 | 17 | 0.589 | 37 | 34 | 0.627 |
| Abell 3653 | $19^h52^m37.92^s$ | -52$^o$74.1" | 106 | 32234$\pm$81 | $836^{+64}_{-52}$ | 1.67 | 50 | 61 | 0.164 | 92 | 123 | 0.044 |
| Abell 3716 | $20^h51^m16.56^s$ | -52$^o$2503.4" | 124 | 13517$\pm$74 | $825^{+58}_{-48}$ | 1.65 | 110 | 113 | 0.226 | 196 | 365 | <0.001 |
| Abell 3744 | $21^h7^m13.80^s$ | -25$^o$1733.7" | 69 | 11483$\pm$72 | $596^{+59}_{-45}$ | 1.19 | 64 | 88 | 0.066 | 88 | 129 | 0.007 |

[a]Redshifts for this sample are sourced from: Fairall 1988; Teague et al. 1990; da Costa et al. 1991; Dalton et al. 1994; Collins et al. 1995; Postman & Lauer 1995; Quintana et al. 1995; Loveday et al. 1996; Quintana & Ramirez 1996; Shectman et al. 1996; Caldwell & Rose 1997; da Costa et al. 1998; Katgert et al. 1998; Vettolani et al. 1998; Wegner et al. 1999; Schindler 2000; Bardelli et al. 2001; Colless et al. 2001; Donnelly et al. 2001; Christlein & Zabludoff 2003; Kaldare et al. 2003; Paturel et al. 2003; Jones et al. 2004; Smith et al. 2004; Pimbblet et al. 2006.

[b]This is the number of NED galaxies within 30 arcmin used to compute $cz$ and $\sigma$ from.

cluster members from a relatively large radius away from this centre. The resultant number of galaxies and values for $R_v$ for each of the clusters are given in Tables 1 & 2.

There are a number of statistical tools available to assess the degree of subclustering in each cluster, ranging from 2 dimensional searches for asymmetry (e.g. West et al. 1988) and bimodality (e.g. Fitchett & Webster 1987) to more complex 3 dimensional tests (e.g. Dressler & Shectman 1988; among others). Given all these different tools, Pinkney et al. (1996) made extensive tests to determine the relative merits of these tools and concluded that the Dressler & Shectman (1988) $\Delta$ test is the best one to use to find substructure in arbitrary cases. Its only real limitation is an insensitivity to equal mass mergers in the plane of the sky and superpositions of sub-groups (Pinkney et al. 1996). Both of these situations would require special and unusual lines of sight to the cluster and are therefore considered to be rare events. Importantly for this study, the DS test will be able to detect substructure in 3:1 mergers with reasonable confidence (circa 95%) down to a sample size of even 30 galaxies (Fig. 27 in Pinkney et al. 1996). At a sample size of >60, this confidence rapidly grows to >99%.

We therefore proceed by applying the Dressler & Shectman (1988) approach to each of our clusters and we refer the reader to that publication for details of its algorithmic execution. For the purposes of this work, it is sufficient to note that if there is little or no substructure, then we may expect the resultant $\Delta$ statistic to be of approximately the same value as the number of galaxies sampled. The final parameter of merit is then $P(\Delta)$ which gives the probability of the observed value of $\Delta$ occurring randomly when the redshifts of cluster members are randomly assigned to other members in a Monte Carlo fashion (i.e. very low values of $P(\Delta)$ indicate the presence of substructure).

Values of $\Delta$ and $P(\Delta)$ are computed for each cluster within radial limits of both $R_V$ and $2R_V$ (Tables 1 & 2). The reason for looking at both these radii is that it may be possible that the $\Delta$ statistic is insensitive to substructure at small ($< 2$Mpc) radii (Pinkney et al. 1996). We also plot the 'bubble plots' in Figure 2 for the results of the DS test for the dumbbell sample. In these plots, substruture can be interpreted as spatially close overlapping circles (Dressler & Shectman 1988). Within $R_V$, we find that the fraction of clusters with certain substructure (i.e. $P(\Delta) < 0.001$) is 2/13 (15%) for the dumbbell sample and 1/14 (7%) for the control sample. At $2R_V$, these fractions change to 5/13 (39%) and 4/14 (29%) respectively (in addition, a further two of control clusters are very close to being considered as having subclustering). We consider the difference in subclustering fractions between the two cluster samples to be statistically insignificant.

This is somewhat surprising as we may have naively expected there to have been recent cluster activity in these dumbbell cluster systems (cf. Quintana et al. 1996) compared to the general cluster population. We re-emphasize the caveat of the DS test limitations: with some of our clusters (size$\sim$ 30), the confidence level in the $\Delta$ statistic may drop to only 95% to be able to detect a 3:1 merger (Pinkney et al. 1996) – $\sim$5 clusters at radii$< R_V$ and $\sim 1$ cluster at $< 2R_V$ in the dumbbell sample; and similar numbers in the control sample. Even with this confidence level and sample sizes, the data suggest that the incidence of 3:1 mass mergers is equal in both samples. Given that Quintana et al. (1996) demonstrate that each component of the dumbbell in NGC 4782/3 system occupies different sub-groups, it is therefore a natural next step to ask whether the other galaxies in our samples also have large peculiar velocities?

# 4 Peculiar Velocities

Pimbblet et al. (2006) have already noted that the dumbbell BCM galaxy from Abell 3653 has a very large peculiar velocity relative to the cluster frame (for both components of the dumbbell – Fig 1). Using the positions of the individual dumbbell components given by Gregorini et al. (1994), we compare each of their redshifts with the mean cluster velocity from Table 1. The results of this are displayed in Table 3. The error listed on the velocity offset, $\Delta cz$, in this Table is simply the mean cluster velocity error (Table 1) added in quadrature to the galaxy velocity error given by NED (where more than 1 redshift measurement of a given dumbbell component is available, we choose the most recent since there is some uncertainty concerning which redshift may refer to what component in older measurements; e.g. Green et al. 1988). We perform a similar analysis on the control sample, identifying the BCM by eye and a magnitudinal comparison using NED (see Table 4).

For the control sample, we find that 3/14 (21%) of the clusters have BCMs with significant peculiar velocities (i.e. $> 3$ standard errors away from $|\Delta cz| = 0$). Meanwhile in the dumbbell sample, 8/13 (62%) clusters have at least 1 dumbbell component with significant peculiar velocities (7 of which are large, $> 300$kms$^{-1}$); but consistent to the control sample, only 3/13 (23%) have *both* dumbbell components with significant peculiar velocities. We note that for Abell 0533 the two dumbbell components have a very significant velocity offset ($> 1600$ kms$^{-1}$!) which questions whether this system should be considered as a proper dumbbell system. Notwithstanding Abell 0533, we suggest that a cluster with a BCM dumbbell system is more likely to possess a significant peculiar velocity in at least one of the dumbbell components than a non-dumbbell BCM cluster. Save for Abell 0533, no peculiar velocity is beyond 1.1 times the velocity dispersion measurement of the clusters, very much inline with the results of Valentijn & Casertano (1988).

# 5 Discussion and Conclusions

Even though the dumbbell sample is a collection of redshifts from many disparate sources, we believe that we have assembled a sufficient quantity of (bright) cluster members to adequately map out each of the clusters to a similar level found in 2dFGRS (cf. Tables 1 & 2). Although the sample is likely not an op-

Table 2: The control cluster sample.

| Cluster | RA (J2000) | Dec (J2000) | $cz$ (kms$^{-1}$) | $\sigma$ (kms$^{-1}$) | $R_V$ (Mpc) | N$_{R_V}$ | $\Delta_{R_V}$ | P$(\Delta)_{R_V}$ | N$_{2R_V}$ | $\Delta_{2R_V}$ | P$(\Delta)_{2R_V}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Abell 2734 | $0^h11^m19.44^s$ | -28$^o$3099.6" | $18646 \pm 94$ | $1038^{+73}_{-84}$ | 2.08 | 120 | 153 | 0.127 | 214 | 427 | <0.001 |
| Abell 2751 | $0^h16^m19.92^s$ | -31$^o$1314.0" | $31863 \pm 103$ | $763^{+80}_{-95}$ | 1.47 | 43 | 67 | 0.014 | 99 | 128 | 0.027 |
| Abell 2755 | $0^h17^m34.80^s$ | -35$^o$669.6" | $28469 \pm 135$ | $829^{+102}_{-129}$ | 1.66 | 29 | 21 | 0.844 | 64 | 87 | 0.180 |
| Abell 2798 | $0^h37^m27.12^s$ | -28$^o$1886.4" | $33516 \pm 108$ | $739^{+84}_{-102}$ | 1.48 | 41 | 60 | 0.008 | 77 | 120 | 0.004 |
| Abell 2811 | $0^h42^m8.88^s$ | -28$^o$1933.2" | $32557 \pm 168$ | $988^{+126}_{-162}$ | 1.98 | 83 | 111 | 0.193 | 175 | 264 | <0.001 |
| Abell 2829 | $0^h51^m19.20^s$ | -28$^o$1868.4" | $33565 \pm 123$ | $793^{+94}_{-117}$ | 1.59 | 39 | 50 | 0.043 | 69 | 118 | 0.010 |
| Abell 3027 | $2^h30^m51.12^s$ | -33$^o$349.2" | $23166 \pm 97$ | $907^{+76}_{-88}$ | 1.81 | 85 | 111 | 0.041 | 166 | 233 | 0.002 |
| Abell 0389 | $2^h51^m28.80^s$ | -24$^o$3416.4" | $34085 \pm 118$ | $667^{+90}_{-115}$ | 1.33 | 26 | 24 | 0.632 | 45 | 55 | 0.173 |
| Abell 3094 | $3^h11^m25.18^s$ | -26$^o$3240.0" | $20475 \pm 77$ | $774^{+61}_{-70}$ | 1.55 | 89 | 110 | 0.084 | 140 | 233 | <0.001 |
| Abell 0957 | $10^h13^m49.80^s$ | -0$^o$3254.4" | $13623 \pm 79$ | $722^{+63}_{-73}$ | 1.44 | 77 | 95 | 0.084 | 115 | 149 | 0.065 |
| Abell 1651 | $12^h59^m24.00^s$ | -4$^o$680.4" | $25152 \pm 107$ | $817^{+83}_{-99}$ | 1.63 | 90 | 127 | 0.194 | 173 | 218 | 0.213 |
| Abell 1750 | $13^h30^m49.68^s$ | -1$^o$3110.4" | $25647 \pm 113$ | $981^{+88}_{-104}$ | 1.96 | 101 | 168 | <0.001 | 193 | 296 | <0.001 |
| Abell 2597 | $23^h25^m16.68^s$ | -12$^o$446.4" | $24691 \pm 117$ | $597^{+117}_{-90}$ | 1.19 | 21 | 16 | 0.529 | 36 | 37 | 0.276 |
| Abell S1136 | $23^h36^m14.76^s$ | -31$^o$2156.4" | $18688 \pm 92$ | $617^{+72}_{-87}$ | 1.23 | 38 | 51 | 0.097 | 55 | 79 | 0.025 |

Table 3: Peculiar velocities of the dumbbells.

| Dumbbell Component | RA (J2000) | Dec (J2000) | $\lvert\Delta cz\rvert$ (kms$^{-1}$) | Significance |
|---|---|---|---|---|
| Abell 2860 1 | $1^h4^m50.13^s$ | -39$^o$2749.6” | 539±110 | 4.90 |
| ” ” 2 | $1^h4^m50.11^s$ | -39$^o$2749.8” | 634±(97)[a] | (6.54)[a] |
| Abell 2911 1 | $1^h26^m5.42^s$ | -37$^o$3472.9” | 143±120 | 1.19 |
| ” ” 2 | uncertain | uncertain | uncertain[b] | – |
| Abell 3151 1 | $3^h40^m26.94^s$ | -28$^o$2437.5” | 376±132 | 2.85 |
| ” ” 2 | $3^h40^m25.14^s$ | -28$^o$2439.0” | 426±128 | 3.33 |
| Abell 3266 1 | $4^h31^m13.29^s$ | -61$^o$1631.8” | 247±103 | 2.40 |
| ” ” 2 | $4^h31^m12.18^s$ | -61$^o$1635.1” | 114±101 | 1.13 |
| Abell 0533 1 | $5^h1^m8.29^s$ | -22$^o$2095.5” | 255±241 | 1.06 |
| ” ” 2 | $5^h1^m6.63^s$ | -22$^o$2096.2” | 1906±230 | 8.29 |
| Abell 3391 1 | $6^h26^m20.22^s$ | -53$^o$2494.0” | 489±133 | 3.68 |
| ” ” 2 | $6^h26^m17.80^s$ | -53$^o$2489.4” | 68±142 | 0.48 |
| Abell 3528 1 | $12^h54^m23.40^s$ | -29$^o$64.8” | 100±107 | 0.93 |
| ” ” 2 | $12^h54^m22.32^s$ | -29$^o$46.8” | 0±101 | 0.00 |
| Abell 3532 1 | $12^h57^m21.96^s$ | -30$^o$1308.9” | 257±64 | 4.02 |
| ” ” 2 | $12^h57^m19.80^s$ | -30$^o$1312.9” | 36±67 | 0.54 |
| Abell 3535 1 | $12^h57^m55.44^s$ | -28$^o$1720.0” | 485±92 | 5.27 |
| ” ” 2 | $12^h57^m54.72^s$ | -28$^o$1728.0” | 462±75 | 6.16 |
| Abell 3570 1 | $13^h46^m47.28^s$ | -37$^o$3268.4” | 24±111 | 0.22 |
| ” ” 2 | $13^h46^m46.92^s$ | -37$^o$3282.4” | 49±120 | 0.41 |
| Abell 3653 1 | $19^h53^m3.48^s$ | -52$^o$133.2” | 736±105 | 7.01 |
| ” ” 2 | $19^h53^m2.76^s$ | -52$^o$134.6” | 495±126 | 3.93 |
| Abell 3716 1 | $20^h52^m0.48^s$ | -52$^o$2718.0” | 559±92 | 6.08 |
| ” ” 2 | $20^h51^m56.88^s$ | -52$^o$2710.8” | 255±88 | 2.90 |
| Abell 3744 1 | $21^h7^m25.68^s$ | -25$^o$1543.3” | 27±94 | 0.29 |
| ” ” 2 | $21^h7^m24.60^s$ | -25$^o$1557.0” | 211±75 | 2.81 |

[a]Redshift error not recorded for this component – the error quoted is simply the error on the cluster mean velocity and should therefore be taken as a lower bound.
[b]Unable to unambiguously distinguish the second component and its redshift from the first component.

Table 4: BCM peculiar velocities in the control sample.

| Cluster | BCM RA (J2000) | BCM Dec (J2000) | $\lvert\Delta cz\rvert$ (kms$^{-1}$) | Significance |
|---|---|---|---|---|
| Abell 2734 | $0^h11^m21.67^s$ | -28$^o$3075.8” | 171±101 | 1.69 |
| Abell 2751 | $0^h16^m13.65^s$ | -31$^o$1392.1” | 245±261 | 0.94 |
| Abell 2755 | $0^h17^m40.99^s$ | -35$^o$720.7” | 284±224 | 1.27 |
| Abell 2798 | $0^h37^m32.20^s$ | -28$^o$1915.9” | 249±116 | 2.15 |
| Abell 2811 | $0^h42^m8.83^s$ | -28$^o$1928.8” | 23±179 | 0.13 |
| Abell 2829 | $0^h51^m22.53^s$ | -28$^o$1897.5” | 416±126 | 3.30 |
| Abell 3027 | $2^h30^m49.42^s$ | -33$^o$371.8” | 384±132 | 2.91 |
| Abell 0389 | $2^h51^m24.80^s$ | -24$^o$3399.4” | 331±191 | 1.73 |
| Abell 3094 | $3^h11^m25.00^s$ | -26$^o$3351.9” | 75±92 | 0.82 |
| Abell 0957 | $10^h13^m38.28^s$ | -0$^o$3331.8” | 253±95 | 2.66 |
| Abell 1651 | $12^h59^m22.56^s$ | -4$^o$706.3” | 419±111 | 3.97 |
| Abell 1750 | $13^h30^m50.76^s$ | -1$^o$3097.0” | 441±116 | 3.80 |
| Abell 2597 | $23^h25^m19.92^s$ | -12$^o$446.0” | 189±118 | 1.60 |
| Abell S1136 | $23^h36^m16.56^s$ | -31$^o$2169.3” | 19±112 | 0.17 |

timal (homogeneously selected) one, we are nonetheless confident that the results presented would not change significantly with the addition of further observations. Indeed, subtracting a small percentage of galaxies from the better sampled clusters produces no significant change in the measured peculiar velocities, or substructuring.

Our results show that dumbbell BCM clusters are no more or less likely than other clusters to possess (3:1) subclustering (cf. Oegerle & Hill 2001). However, they are more likely to have at least one BCM component with a significant peculiar velocity. We suggest the unifying interpretation of these observations is that our dumbbell BCM clusters may be in various states of post-merger activity. Those with both subclustering and peculiar velocities (e.g. Abell 3391) are probably in the early stages of mixing: the bulk of the galaxies are separable in to sub-groups with a dumbbell component belonging to one (or even each) sub-grouping (cf. Quintana et al. 1996). As the merger progresses, we may expect the less massive galaxies to homogenize first eventually leaving only a large peculiar velocity in one or both dumbbell components as the singular signpost to recent cluster activity, before the individual components of the dumbbell BCM itself relax with respect to each other and the rest of the merged cluster (Abell 2911). Alternatively, we note that intermediate clusters such as Abell 3570 may simply be the result of ellipticals preferentially being on radial orbits (e.g. Ramirez & de Souza 1998; see also Hwang & Lee 2008) and hence observationally indistinguishable. The dumbbell itself may be a final transient phase before ultimately merging into a more massive cD-like galaxy (e.g. Tremaine 1990; West 1994). These results and the emerging picture of the evolution of dumbbells with respect to cluster substructure are also consistent with other observational evidence that the timescale for clusters to accrete new galaxies is much shorter than the timescale required for the central galaxy to merge with the accreted galaxies (e.g. Cooray & Milosavljević 2005; Brough et al. 2008).

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## References

Abell, G. O. 1958, ApJS, 3, 211

Abell, G. O., Corwin, H. G., Jr., & Olowin, R. P. 1989, ApJS, 70, 1

Bardelli, S., Zucca, E., & Baldi, A. 2001, MNRAS, 320, 387

Brough, S., Couch, W. J., Collins, C. A., Jarrett, T., Burke, D. J., & Mann, R. G. 2008, MNRAS, 385, L103

Caldwell, N., & Rose, J. A. 1997, AJ, 113, 492

Christlein, D., & Zabludoff, A. I. 2003, ApJ, 591, 764

Colless, M., et al. 2001, MNRAS, 328, 1039

Collins, C. A., Guzzo, L., Nichol, R. C., & Lumsden, S. L. 1995, MNRAS, 274, 1071

Cooray, A., & Milosavljević, M. 2005, ApJL, 627, L85

da Costa, L. N., Pellegrini, P. S., Davis, M., Meiksin, A., Sargent, W. L. W., & Tonry, J. L. 1991, ApJS, 75, 935

da Costa, L. N., et al. 1998, AJ, 116, 1

Cruddace, R., et al. 2002, ApJS, 140, 239

Dalton, G. B., Efstathiou, G., Maddox, S. J., & Sutherland, W. J. 1994, MNRAS, 269, 151

De Propris, R., et al. 2002, MNRAS, 329, 87

Donnelly, R. H., Forman, W., Jones, C., Quintana, H., Ramirez, A., Churazov, E., & Gilfanov, M. 2001, ApJ, 562, 254

Dressler, A., & Shectman, S. A. 1988, AJ, 95, 985

Dubinski, J. 1998, ApJ, 502, 141

Ebeling, H., Voges, W., Bohringer, H., Edge, A. C., Huchra, J. P., & Briel, U. G. 1996, MNRAS, 281, 799

Ebeling, H., Barrett, E., Donovan, D., Ma, C.-J., Edge, A. C., & van Speybroeck, L. 2007, ApJL, 661, L33

Fairall, A. P. 1988, MNRAS, 233, 691

Fitchett, M., & Webster, R. 1987, ApJ, 317, 653

Girardi, M., Biviano, A., Giuricin, G., Mardirossian, F., & Mezzetti, M. 1993, ApJ, 404, 38

Girardi, M., Giuricin, G., Mardirossian, F., Mezzetti, M., & Boschin, W. 1998, ApJ, 505, 74

Gregorini, L., Vettolani, G., de Ruiter, H. R., & Parma, P. 1992, A&AS, 95, 1

Gregorini, L., de Ruiter, H. R., Parma, P., Sadler, E. M., Vettolani, G., & Ekers, R. D. 1994, A&AS, 106, 1

Green, M. R., Godwin, J. G., & Peach, J. V. 1988, MNRAS, 234, 1051

Hoessel, J. G., & Schneider, D. P. 1985, AJ, 90, 1648

Hwang, H. S., & Lee, M. G. 2008, ApJ, 676, 218

Jones, D. H., et al. 2004, MNRAS, 355, 747

Kaldare, R., Colless, M., Raychaudhury, S., & Peterson, B. A. 2003, MNRAS, 339, 652

Katgert, P., Mazure, A., den Hartog, R., Adami, C., Biviano, A., & Perea, J. 1998, A&AS, 129, 399

Lacey, C., & Cole, S. 1993, MNRAS, 262, 627

Laine, S., van der Marel, R. P., Lauer, T. R., Postman, M., O'Dea, C. P., & Owen, F. N. 2003, AJ, 125, 478

Lauer, T. R. 1988, ApJ, 325, 49

Loveday, J., Peterson, B. A., Maddox, S. J., & Efstathiou, G. 1996, ApJS, 107, 201

Merritt, D. 1985, ApJ, 289, 18

Oegerle, W. R., & Hill, J. M. 2001, AJ, 122, 2858

Ostriker, J. P., & Tremaine, S. D. 1975, ApJL, 202, L113

Paturel, G., Theureau, G., Bottinelli, L., Gouguenheim, L., Coudreau-Durand, N., Hallet, N., & Petit, C. 2003, A&A, 412, 57

Pimbblet, K. A., Roseboom, I. G., & Doyle, M. T. 2006, MNRAS, 368, 651

Pinkney, J., Roettiger, K., Burns, J. O., & Bird, C. M. 1996, ApJS, 104, 1

Postman, M., & Lauer, T. R. 1995, ApJ, 440, 28

Quintana, H., Ramirez, A., Melnick, J., Raychaudhury, S., & Slezak, E. 1995, AJ, 110, 463

Quintana, H., Ramirez, A., & Way, M. J. 1996, AJ, 112, 36

Ramirez, A. C., & de Souza, R. E. 1998, ApJ, 496, 693

Scaramella, R., Zamorani, G., Vettolani, G., & Chincarini, G. 1991, AJ, 101, 342

Shectman, S. A., Landy, S. D., Oemler, A., Tucker, D. L., Lin, H., Kirshner, R. P., & Schechter, P. L. 1996, ApJ, 470, 172

Schindler, S. 2000, A&AS, 142, 433

Smith, R. J., et al. 2004, AJ, 128, 1558

de Souza, R., & Quintana, H. 1990, AJ, 99, 1065

Teague, P. F., Carter, D., & Gray, P. M. 1990, ApJS, 72, 715

Tremaine, S. 1990, Dynamics and Interactions of Galaxies, 394

Valentijn, E. A., & Casertano, S. 1988, A&A, 206, 27

Vettolani, G., et al. 1998, A&AS, 130, 323

Wegner, G., Colless, M., Saglia, R. P., McMahan, R. K., Davies, R. L., Burstein, D., & Baggley, G. 1999, MNRAS, 305, 259

West, M. J., Oemler, A. J., & Dekel, A. 1988, ApJ, 327, 1

West, M. J. 1994, MNRAS, 268, 79

Woudt, P. A., Kraan-Korteweg, R. C., Lucey, J., Fairall, A. P., & Moore, S. A. W. 2008, MNRAS, 383, 445

Yamada, T., Koyama, Y., Nakata, F., Kajisawa, M., Tanaka, I., Kodama, T., Okamura, S., & De Propris, R. 2002, ApJL, 577, L89

Zabludoff, A. I., Huchra, J. P., & Geller, M. J. 1990, ApJS, 74, 1

Zabludoff, A. I., Geller, M. J., Huchra, J. P., & Ramella, M. 1993, AJ, 106, 1301

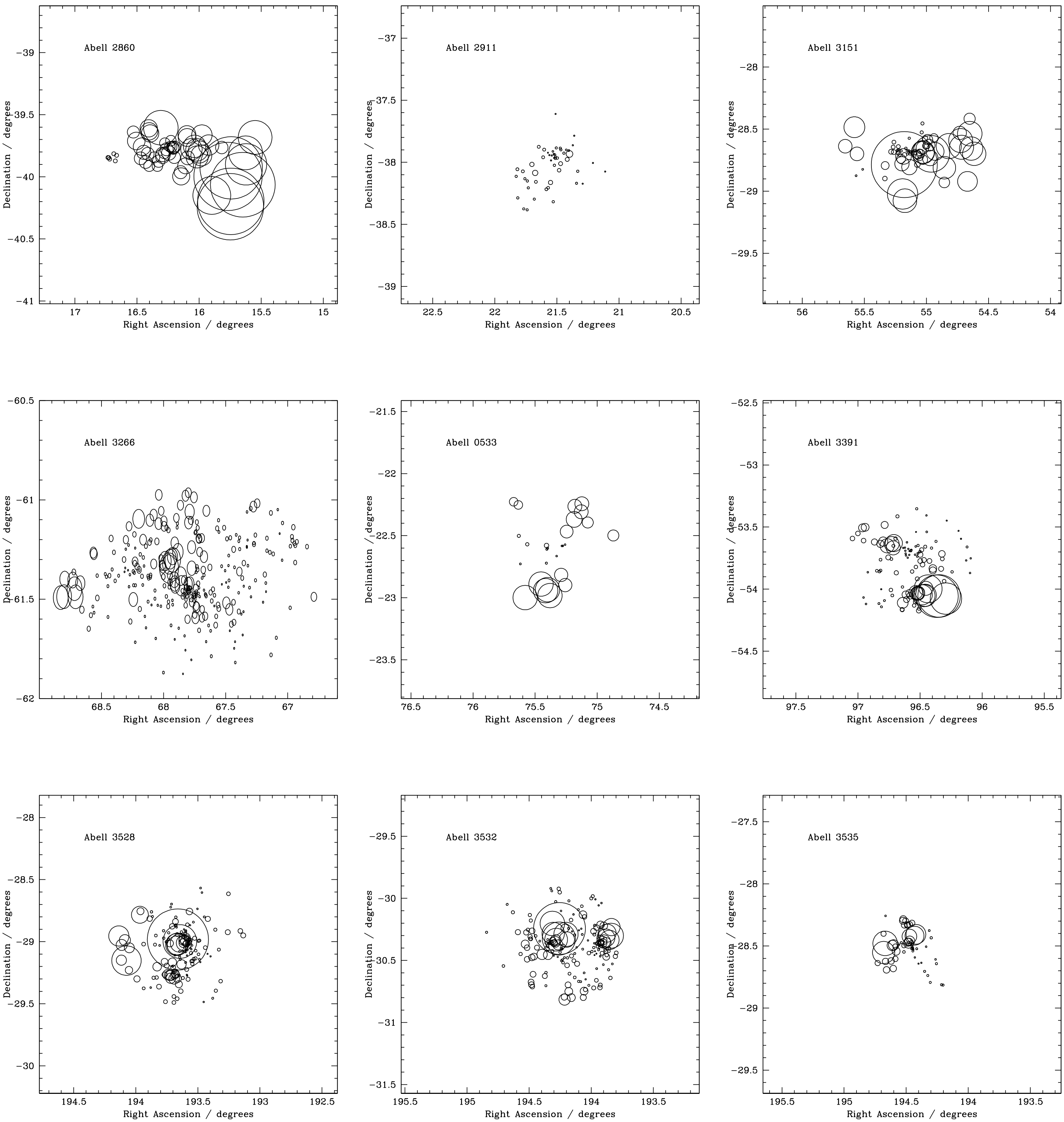


Figure 2: Results of applying the DS test to the dumbbell sample. In these bubble plots, each circle's radius is scaled proportional to the Dressler & Shectman (1988) $\delta$ statistic (i.e. proportional to the deviation of a localized group of galaxies mean velocity away from the whole cluster's mean velocity). Substruture is therefore indicated by spatially close and relatively big overlapping circles.

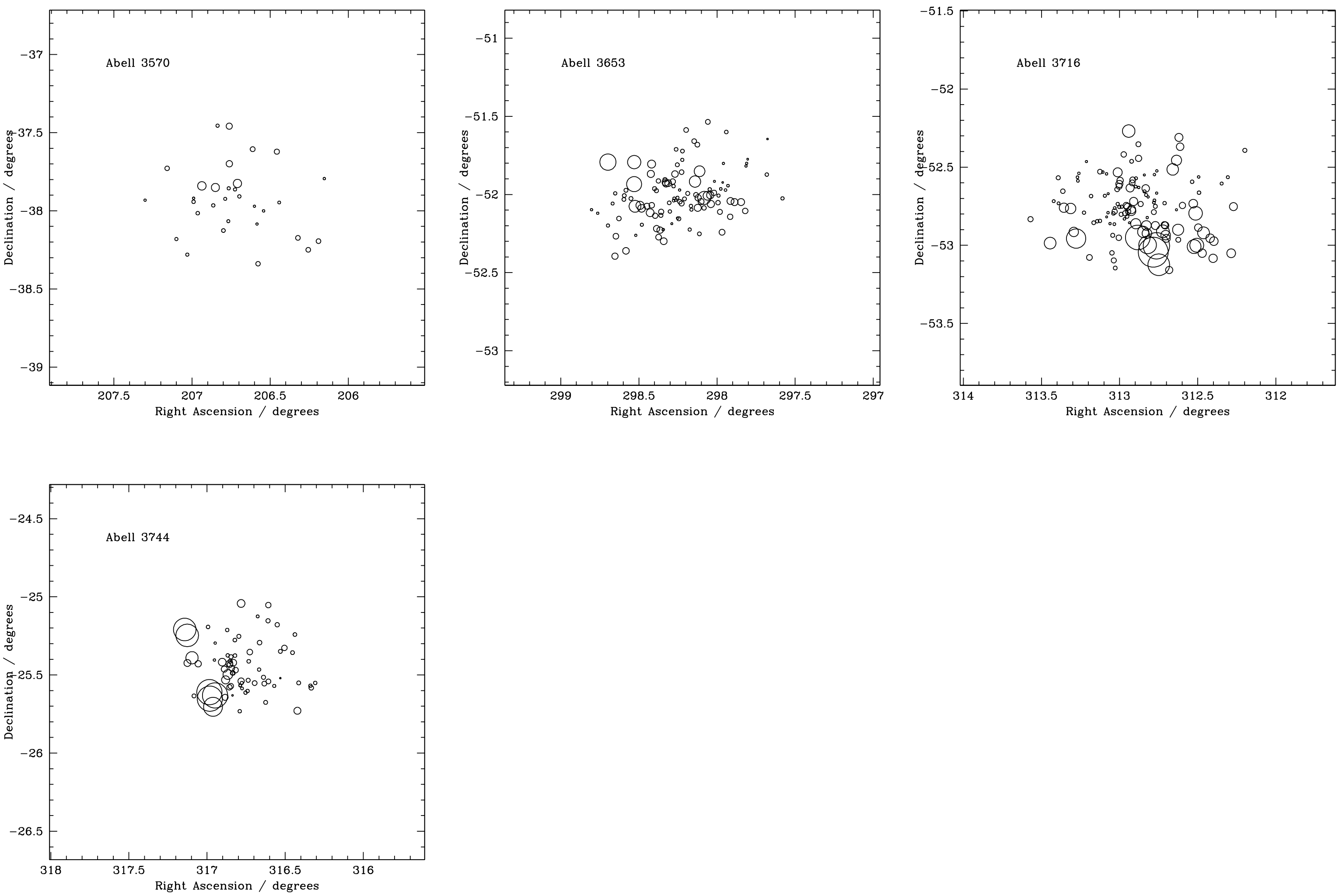


Figure 2: continued.